

Top Quark Yukawa Couplings and New Physics

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Abstract.

We discuss associated production of a Higgs boson with a pair of $t\bar{t}$ quarks at a future high energy e^+e^- collider. The process $e^+e^- \rightarrow t\bar{t}h$ is particularly sensitive to the presence of new physics and we consider the MSSM and models with extra dimensions at the TeV scale as examples.

INTRODUCTION

The present and next generation of colliders will help elucidate the nature of the electroweak symmetry breaking and to determine if the symmetry breaking is due to the presence of a Higgs boson. Precision fits of the Standard Model seem to indirectly point at the existence of a light Higgs boson ($M_h < 170 - 210$ GeV) [1], while the Minimal Supersymmetric Standard Model (MSSM) requires the existence of a scalar Higgs lighter than about 130 GeV. Thus, a Higgs discovery by the Tevatron or the LHC in the mass range around 120 – 130 GeV seems a likely possibility. The role of the next generation of e^+e^- colliders will therefore not be to make a Higgs discovery, but rather to obtain precision measurements of the Higgs properties and to use them to understand the underlying mechanism of electroweak symmetry breaking.

The production of a Higgs boson in association with a pair of $t\bar{t}$ quarks is of particular interest for two reasons. First, the $t\bar{t}h$ production mode can be an important discovery mode for a Higgs boson around 120 – 130 GeV at the LHC [2] or the Tevatron [3]. Second, this channel offers a direct handle on the Yukawa coupling of the top quark to the Higgs boson.

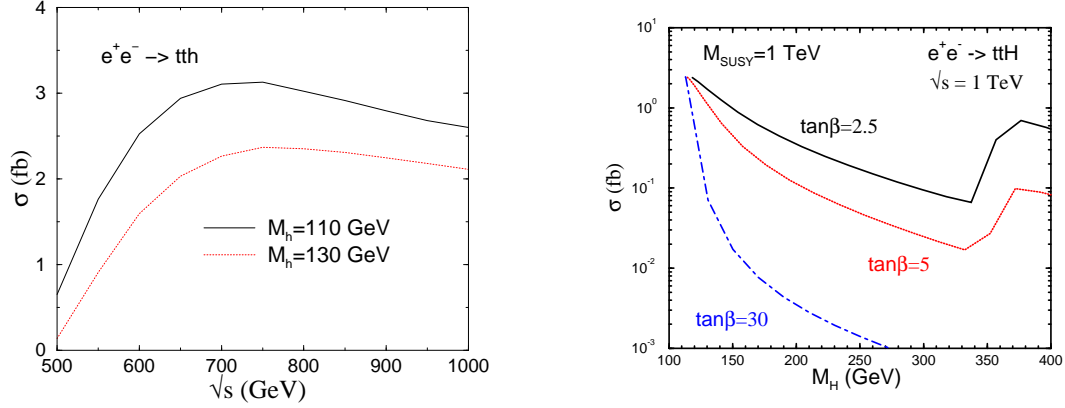


FIGURE 1. *Left plot:* Standard Model cross section for $t\bar{t}h$ production as a function of the center of mass energy, \sqrt{s} . *Right plot:* Cross section for $e^+e^- \rightarrow t\bar{t}H$, where H is the heavier of the neutral Higgs bosons of the MSSM.

I ASSOCIATED TOP-HIGGS PRODUCTION AT A HIGH ENERGY E^+E^- COLLIDER

The process $e^+e^- \rightarrow t\bar{t}h$ has been studied extensively and has been calculated both in the SM and in the MSSM at $O(\alpha_s)$ [4,5]. For a SM Higgs, the factor $K = \sigma_{NLO}/\sigma_{LO}$ at $\sqrt{s}=500$ GeV is in the range (1.4 – 2.4), depending on M_h . However the cross section is drastically suppressed by phase space and for $M_h \simeq 120 - 130$ GeV is of the order of 0.1 fb. On the other hand, at $\sqrt{s}=1$ TeV the cross section for $M_h=120 - 130$ GeV is about 2 fb and is only slightly reduced by QCD corrections ($K = 0.8 - 0.9$). The energy dependence of the rate is shown in Fig. 1 and it is clear that the optimal energy is somewhere around $\sqrt{s} \sim 700 - 800$ GeV.

Although the cross section is small, the signature for $t\bar{t}h$ production is spectacular. The possibility of fully reconstructing the two top quarks in the final state allows efficient discrimination of the signal over the background, and together with a good b-tagging efficiency is crucial for increasing the precision with which the top Yukawa coupling can be measured. A detailed simulation [6] of $e^+e^- \rightarrow t\bar{t}h$ for a 120 GeV Higgs, at $\sqrt{s}=800$ GeV, found that the top Yukawa coupling could potentially be measured with a precision of 5.5% when optimal b-tagging efficiency is assumed. At lower energies, and for heavier Higgs masses, the precision deteriorates rapidly. [7]

II MSSM

Associated production of a Higgs boson and a $t\bar{t}$ pair in the MSSM can be very different from the Standard Model since the $t\bar{t}h$ coupling can be significantly suppressed for small M_A , (where h is now the lightest neutral Higgs boson of the MSSM). In addition, the presence of additional Higgs bosons leads to the possibility

of new processes and of resonance effects. An example is $e^+e^- \rightarrow AH \rightarrow t\bar{t}H$, which is illustrated in the right hand plot of Fig. 1. (H is the heavier of the neutral Higgs bosons of the MSSM). The resonance at $2M_t$ is apparent. The main channels in the MSSM are the scalar ones, i.e. $t\bar{t}h$ and $t\bar{t}H$, since the pseudoscalar mode $t\bar{t}A$ is very suppressed over most of the MSSM parameter space. Over most of the $\tan\beta - M_A$ plane, it is possible to observe either $t\bar{t}h$ or $t\bar{t}H$ with a rate greater than 1 fb at $\sqrt{s} = 500 \text{ GeV}$. [4]

III MODELS WITH EXTRA DIMENSIONS AT THE TEV SCALE

Scenarios such as that proposed by Arkani-Hamed, Dimopoulos, and Dvali, [8] (ADD) in which gravity propagates in $d+4$ dimensions can have a dramatic effect on Higgs physics. In such models the gravitational interactions occur at a scale M_S , which can be as small as a TeV . The extra d dimensions are then compactified on a torus of radius R . This leads to a relationship between Newton's Constant, G_N , and the other scales,

$$\frac{1}{G_N} \sim R^d M_S^{d+2} \quad . \quad (1)$$

These models have a tower of very light Kaluza Klein excitations which couple weakly to ordinary matter ($\sim 1/M_{pl}$). However, the density of the light Kaluza Klein modes is high (for large R) and so the collective interactions build up to electroweak strength. At tree level, the contributions of the spin-0 Kaluza Klein modes to $e^+e^- \rightarrow t\bar{t}H$ are suppressed by m_e , so only the spin 2 states are relevant here.

It is straightforward to find the effective 4-fermion and $f\bar{f}hh$ interactions due to the graviton exchanges which contribute to $e^+e^- \rightarrow t\bar{t}h$. [9] For $f(p) + \bar{f}(q) \rightarrow f'(p') + \bar{f}'(q')$, we have

$$\begin{aligned} \mathcal{A}_{ffff} = \frac{C(s)}{16} & \left\{ \bar{v}(q)(\not{p}' - \not{q}')u(p)\bar{v}(p')(\not{p} - \not{q})v(q') \right. \\ & \left. + (p - q) \cdot (p' - q')\bar{u}(q)\gamma^\mu u(p)\bar{u}(p')\gamma_\mu v(q') \right\} \quad , \end{aligned} \quad (2)$$

while for $f(p) + \bar{f}(q) \rightarrow h(p_{h1}) + h(p_{h2})$, the effective interaction is,

$$\mathcal{A}_{ffhh} = \frac{C(s)}{2}(p - q) \cdot p_{h1}\bar{v}(q)\not{p}_{h1}u(p) \quad . \quad (3)$$

The constant $C(s)$ represents the effect of the sum over all the Kaluza Klein modes (with masses M_i) and is given by [9]

$$C(s) = -16\pi G_N \sum_i \frac{1}{s - M_i^2} \xrightarrow{(\sqrt{s} < M_S, d > 2)} \frac{16\pi}{d - 2} \left(\frac{1}{M_S} \right)^4 \quad . \quad (4)$$

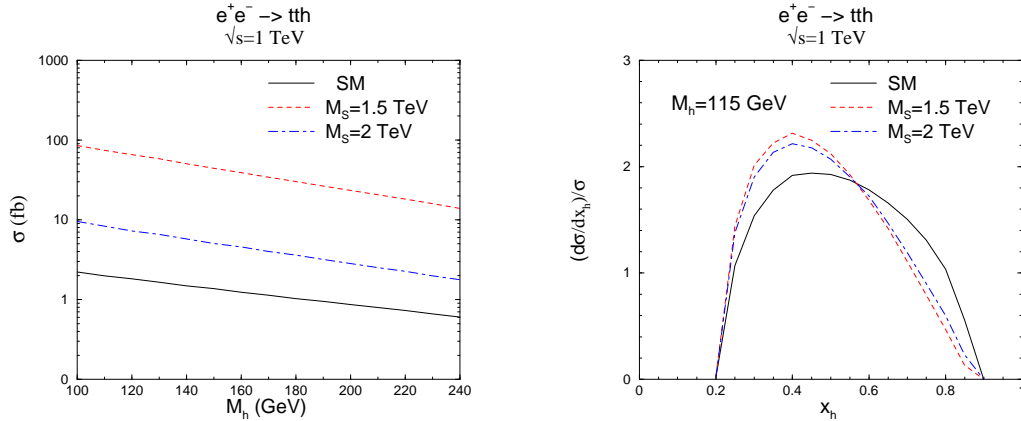


FIGURE 2. *Left plot:* Cross section for $t\bar{t}h$ production in the ADD model with $d = 3$ extra dimensions and where gravitational interactions occur at the scale M_S . *Right plot:* Energy distribution of the Higgs boson in the ADD model.

Calculating the complete rate for $e^+e^- \rightarrow t\bar{t}h$, including the Standard Model interactions, the new interactions of Eqs. (2) and (3), and the relevant interference terms, gives the rates in the ADD scenario shown in Fig. 2 for $d = 3$ extra dimensions. At $\sqrt{s} = 1$ TeV, the rate can be enhanced by several orders of magnitude if the gravitational interactions are at the 1 – 2 TeV scale. The energy distribution of the Higgs boson, $x_h = 2E_h/\sqrt{s}$, is slightly shifted to lower values of x_h by the presence of the gravitational interactions.

IV CONCLUSION

The process $e^+e^- \rightarrow t\bar{t}h$ provides a sensitive probe of new physics effects. It is best measured at $\sqrt{s} = 700 - 800$ GeV and requires the highest possible luminosity.

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